



Inductive acceleration of UHECRs in sheared relativistic jets

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Abstract: Relativistic outflows carrying large scale magnetic fields have large inductive potential and may accelerate protons to ultra high energies. We discuss a novel scheme of Ultra-High Energy Cosmic Ray (UHECR) acceleration due to drifts in magnetized, cylindrically collimated, sheared jets of powerful active galaxies (with jet luminosity $\geq 10^{46}$ erg s⁻¹). A positively charged particle carried by such a plasma is in an unstable equilibrium if $\mathbf{B} \cdot \nabla \times \mathbf{v} < 0$, so that kinetic drift along the velocity shear would lead to fast, *regular* energy gain. The highest rigidity (ratio of energy to charge) particles are accelerated most efficiently implying the dominance of light nuclei for energies above the ankle in our model: from a mixed population of pre-accelerated particle the drift mechanism picks up and boosts protons preferably.

Introduction

There is a consensus that relativistic outflows, and AGN jets in particular, are accelerated to relativistic speeds and collimated by large scale magnetic fields threading accretion disk and central black hole. Energetically, magnetic fields may carry a large fraction of jet luminosity [1, 3]. At largest scales magnetic field is dominated by a toroidal component B_ϕ . In addition, toroidal magnetic field may provide jet collimation, so that asymptotically AGN jets may also be fully collimated to a cylindrical shape [2]. Axial motion of toroidal magnetic field create radial (in cylindrical coordinates) electric field. One also expects that jets are sheared, so that the central spine of the jet is moving with larger velocity than its periphery. In a sheared jet Lorentz transformation cannot get rid of electric field everywhere in space.

Powerful astrophysical outflows carrying large scale magnetic fields poses large inductive potentials that may be able to accelerate UHECRs [4]. If the Poynting luminosity of a source is L_{EM} , then the total inductive potential is

$$\Phi \sim \sqrt{\frac{4\pi L_{EM}}{c}} = 4 \times 10^{20} \text{V} \left(\frac{L}{10^{46} \text{erg/sec}} \right)^{1/2} \quad (1)$$

Though Poynting luminosity L_{EM} may exceed the observed total luminosity of a source (which is related to the rate of dissipation), the estimate (1) *excludes acceleration of UHECRs in low power AGNs (e.g. Cen A and M87), low power BL Lacs and starburst galaxies (e.g. M82 & NGC 253) and limits the possibilities to more distant high power AGNs like higher power FR I, FR II radiogalaxies, radio-loud quasars and GRBs.*

Another constraint that acceleration sites should satisfy is that radiative losses should not degrade particle energy. We can derive very general constraints on possible location of cosmic ray acceleration just by balancing the most efficient acceleration, by $E \sim B$, and radiative losses. If we normalize total energy density to energy density of magnetic field $u = \zeta u_B$, $\zeta > 1$, we find

$$\mathcal{E} = mc^2 \sqrt{\frac{c}{\zeta r_c Z^3 \omega_B}} \quad (2)$$

where $r_c = e^2/mc^2$. This gives limits on magnetic field and the distance from the central source

$$B < \frac{m^2 c^4}{\zeta Z^3 e^3} \left(\frac{mc^2}{\mathcal{E}} \right)^2 \Gamma^3 = 2 \Gamma^3 \text{G} \left(\frac{\mathcal{E}}{100 \text{EeV}} \right)^{-2} \left(\frac{1}{Z} \right)^3$$

$$R > \frac{Z^2 e^2 \zeta}{mc^2} \left(\frac{\mathcal{E}}{mc^2} \right)^3 \frac{1}{\Gamma^2} = 10^{17} \frac{1}{\Gamma^2} \text{ cm} \left(\frac{\mathcal{E}}{100 \text{ EeV}} \right)^3 (Z)^2 \quad (3)$$

Where we also allowed a possibility that plasma is expanding with bulk Lorentz factor Γ , so that magnetic field in the plasma rest-frame is B/Γ and typical scale is R/Γ , and assumed $\zeta = 1$; $\text{EeV} = 10^{18} \text{ eV}$.

Relations (3) show that higher energy cosmic rays are better accelerated at larger distances. AGN jets, which propagate to more than 100 kpc distances present an interesting possibility. Note, that as long as the jet remains relativistic, the total inductive potential is approximately conserved, so one can “wait” a long time for a particle to get accelerated without worrying about radiative losses. Thus, UHECRs can be accelerated inside the jet at distances from a fraction of a parsec (Eq. (3)) to hundreds of kpc, as long as the jet remains relativistic and sustains a large inductive potential.

Since inductive electric fields are orthogonal to magnetic field, particles cannot move freely along them. Thus, it is not obvious how to achieve energy gain. One possibility is kinetic drift which may result in regular motion across magnetic field and along electric field leading to *regular energy gain* as compared to the stochastic, Fermi-type schemes. Since the drift velocity increases with particle energy, *the rate of energy gain will also increase with particle energy*. Thus, the highest energy particles will be accelerated most efficiently. This means that from a pre-accelerated population, the mechanism proposed here will pick up particles with highest energy and will boost them to even higher values. In addition, when a particle has crossed a considerable fraction of the total available potential, its gyro-radius becomes comparable with flow scale. In this case, drift approximation brakes down. As a result, as long as the particle remains inside a jet, *the acceleration rate reaches the theoretical maximum of an inverse gyro-frequency*. Thus, the most efficient acceleration occurs right before the particle leaves the jet. One may say that in case of inductive acceleration, *becoming unbound is beneficial to acceleration*, contrary to the case of stochastic acceleration when for unbound particles acceleration ceases.

Particle dynamics in sheared flow

In a transversely sheared flow one sign of charges is located at a maximum of electric potential, as we describe in this section. Consider sheared flow carrying magnetic field. At each point there is electric field $\mathbf{E} = -\mathbf{v} \times \mathbf{B}/c$, so that the electric potential is determined by

$$\Delta \Phi = \frac{1}{c} \nabla \cdot (\mathbf{v} \times \mathbf{B}) \quad (4)$$

In a local rest frame, where $\mathbf{v} = 0$, this becomes vanishes at the position of a particle,

$$\Delta \Phi = \frac{1}{c} (\mathbf{B} \cdot \nabla \times \mathbf{v}) \quad (5)$$

Thus, *depending on the sign of the quantity $(\mathbf{B} \cdot \nabla \times \mathbf{v})$ (which is a scalar) charges of one sign are near potential minimum, while those with the opposite sign are near potential maximum*, see Fig. 1. Since electric field is perpendicular both

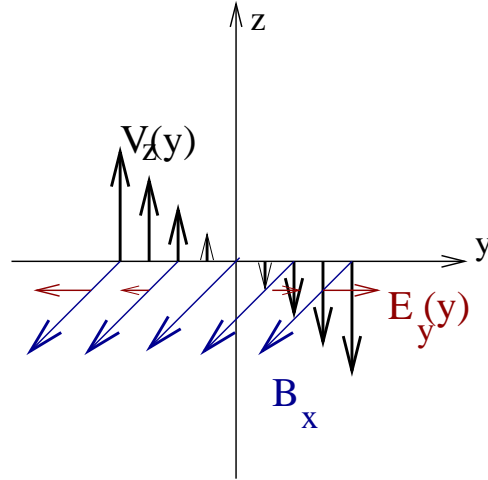


Figure 1: Electric field in a sheared flow in a frame where surface the $y = 0$ is at rest. For $\mathbf{B} \cdot \nabla \times \mathbf{v} < 0$ the electric field is directed away from the $y = 0$ surface.

to velocity and magnetic field, locally, the electric potential is a function of only one coordinate along this direction. For $(\mathbf{B} \cdot \nabla \times \mathbf{v}) < 0$ (we will call this case negative shear) ions are near potential maximum.

Inductive electric fields are not easily accessible for acceleration since particle need to move across

magnetic field, a processes prohibited under ideal Magneto-Hydrodynamics (MHD) approximation. On the other hand, kinetic drifts may result in regular motion across magnetic field and along electric field leading to *regular energy gain*. Typically, the direction of drift is along the normal to the magnetic field and to the direction of the force that induces a drift. In sheared cylindrical jet with toroidal magnetic field, the electric field is in radial direction, so that in order to gain energy particle should experience radial drift. It is then required that there should be a force along the axis. Such force may arise if a jet is axially inhomogeneous, *e.g.* due to propagation of compressible waves along the jet, resulting in gradient drift due to changing magnetic pressure.

Let's assume that there is a long wavelength inertial Alfvén wave propagating along the z -direction with a phase speed V_A . For $V_A \ll c$, the magnetic perturbation δB in the wave is much larger than electric perturbations δE by a factor c/V_A , so that the wave is nearly magneto-static (in other words $\omega \ll k_z c$). A test particle will experience a drift in the x -direction with magnitude

$$u_d \sim \frac{\delta B}{B_0} \frac{\gamma c^2 k_z}{Z \omega_{B,0}} \sim \frac{\gamma c^2 k_z}{Z \omega_{B,0}} \quad (6)$$

where we assumed strong perturbation $\delta B_0 \sim B$ and $\omega_{B,0} = eB_0/mc$. As a particle drifts along electric field in the x -direction its Lorentz factor evolves according to

$$\partial_t \gamma = \frac{ZeE_y u_d}{mc^2} = \beta_0 \frac{Z \omega_{B,0} u_d^2 t}{c L_V} \sim \beta_0 \frac{\gamma^2 c^3 k_z^2 t}{Z \omega_{B,0} L_V} \quad (7)$$

Thus, energy gain or loss of a test particle depends on direction of magnetic field, sign of charge (through ω_B) and direction of velocity vorticity (through sign of L_V): in other words it depends on sign of shear. On the other hand, it is *independent* of the direction of the drift.

Since drift velocity increases with particle energy, the rate of energy gain also increases with energy, see Eq. (7). This leads to one of the most unusual properties of the proposed acceleration mechanisms: *highest energy (or highest rigidity) particles are accelerated most efficiently*. In addition, at the last stages of acceleration, when particle Larmor radius becomes of the order of jet scale,

particle motion in positive shear flow becomes unstable even without gradient drift while *acceleration rate does reach absolute theoretical maximum of inverses relativistic gyro-frequency*.

In addition, since acceleration rate is *inversely* proportional to charge, at a given energy small charge (higher rigidity) particles are accelerated most efficiently. Thus, from a population of pre-accelerated particles with mixed composition, drift mechanism will pick up particles with smallest charge: protons. This explains why above the ankle protons start to dominate over heavy nuclei.

We can also calculate evolution of the spectrum. If the initial injection spectrum is power-law, $f_0 \propto 1/\gamma_0^p$, then

$$\begin{aligned} f(\gamma, t) &\propto \frac{1}{\gamma^p} \left(1 + \gamma \left(\frac{t}{\tau_0} \right)^2 \right)^{p-2} \\ &\sim \gamma^{-2}, \quad \text{for } \gamma t^2 / \tau_0^2 \gg 1 \end{aligned} \quad (8)$$

Thus, for $p > 2$ the spectrum flattens with time.

The hardest spectrum that can be achieved has a power law index of 2. This limiting case corresponds to unlimited acceleration in a plane-parallel geometry, which is realistically applicable to energies well below the total available potential. At highest energies the final spectrum will depend on the distribution of pre-accelerated particles with respect to the electric potential and, in case of contribution from many sources, on distribution of total potentials.

Discussion/predictions

The best astrophysical location for operation of the proposed mechanism is *cylindrically collimated*, high power AGN jets. The proposed mechanism cannot work in spherically (or conically) expanding outflows since in this case a particle experiences polarization drift, which is a *first order* in Larmor radius, due to the fact that in the flow frame magnetic field decreases with time. For a constant velocity flow this drift is always against the electric field (for a positively charged particle) and lead to the decrease of energy on time scale $R/(c\Gamma)$, where R is a distance from the central source and Γ is the Lorentz factor of the

flow. Thus, in spherically expanding flows adiabatic losses always dominate over regular energy gain due to drift motion: the proposed mechanism would fail then. On theoretical grounds, AGN jets (or at least their cores) may indeed be asymptotically cylindrically collimated [2]. Observations of large scale jets, *e.g.* Pictor A, do show jets that seem to be cylindrically collimated on scales of tens of kiloparsec.

In cylindrically collimated parts of the jet acceleration can happen from sub-parsec to hundreds of kiloparsec scales: as long as the motion of the jet is relativistic the total electric potential remains approximately constant. Thus, UHECRs need not be accelerated close to the central black hole where radiative losses are important. After a jet has propagated parsecs from the central source radiative losses become negligible.

Another constraint on the mechanism comes from the requirement that in order to produce radial kinetic drift the jet magnetic field should be inhomogeneous along the axis. Though shocks provide possible inhomogeneity of magnetic field (δ -function inhomogeneity on the shock front), we disfavor shock since particles are advected downstream and cannot drift large distances along shock surface. In a gradual inhomogeneity a particle drifts orthogonally to the field gradients and thus generally will remain in the region of inhomogeneous fields. Extragalactic jets are expected to have axial inhomogeneities, both due to non-stationary conditions at the source and due to propagation of compression and rarefaction waves generated at the jet boundary via interaction with surrounding plasma.

Our model has a number of clear predictions, some of which are related to astrophysical association of acceleration sites of UHECRs with AGN jets [5] and some are specific to the model: (i) one needs a relatively powerful AGN, with luminosity $\geq 10^{46}$ erg/sec. This limits possible sources to high power sources like FR II radiogalaxies, radio loud quasars and high power BL Lacs (flat spectrum radio quasars). Powerful AGNs are relatively rare and far apart, so that a steep GZK cut-off corresponding to large source separation should be seen. (ii) UHECRs come from sources with low spacial density. This may be reflected in the distribution of arrival directions. (iii) Extragalactic UHECRs

should be dominated by protons. (iv) Depending on "extra-galactic seeing conditions" arrival directions of UHECRs may point to their sources, though complicated magnetic field structure may erase this correlation. In addition, the fact that only flows with negative shear can accelerate protons implies that only approximately half of such AGNs can be sources of UHECRs (this assumes that the AGN central engine - black hole or an accretion disk - is dominated by large scale, dipolar-like magnetic field).

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